

DIRECTED-ENERGY PROCESS TECHNOLOGY EFFORTS

JET PROPULSION LABORATORY

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Directed Energy

Definition: Directing energy or mass to specific areas on solar cells to produce an effect

This compares with exposing solar cells to a thermal or mass flow environment to produce an effect

Examples of environmental exposures for cell processing include:

- Thermal diffusion, furnace anneal
- Metal sintering, cleaning, etching
- CVD, belt furnace operations

The above might be considered as first-generation processing

Examples of directed-energy processing include:

- Ion implantation: Pulsed electron beam anneal (PEBA)
Pulsed excimer laser anneal (PELA)
- Laser cutting
- Laser assisted metallization
- Laser-assisted deposition
- Laser drive-in of liquid dopants
- Microwave-enhanced chemical vapor deposition (MECVD)
- Rapid thermal processing (RTP)

The above might be considered as second generation processing

PLENARY SESSIONS

Advantages of Directed Energy and Mass Processing

- **Surface heating**
 - Allows bulk temperature of cell to remain near ambient
 - Thereby preserving bulk lifetime; (laser processing, heat lamps)
- **Better process control:**
Tighter control of process parameters should yield better control of junction profiles, junction depths, metal sintering, etc.
- **Lower process energy costs:**
Energy is used directly on the cell instead of into the total cell environment
- **Less working space:**
 - e.g., laser space versus furnace space
- **Should produce higher-efficiency cells at lower costs**

Disadvantages of directed energy and mass processing

- **High throughput not yet demonstrated**
- **High equipment costs and maintenance costs. Reliability not yet demonstrated**

Directed-Energy Contracts

DOE/FSA has funded the following directed-energy/mass contracts in FY/84/85; Earlier contracts included ion implantation, pulsed electron beam annealing

- **Pulsed excimer laser anneal: special DOE funding, competitively awarded to Spire Corporation, No. 956797 and ARCO Solar, Inc., No. 956831; ARCO also investigating laser-assisted metal and film deposition on No. 956831.**
- **Laser-assisted metallization: Westinghouse, No. 956615**
- **Laser drive-in of liquid dopants: Westinghouse, No. 956616 (rapid thermal processing also investigated)**
- **Microwave-enhanced chemical vapor deposition (MECVD), Superwave Technology, Inc., No. 956828**

PLENARY SESSIONS

Results of Excimer Laser Annealing Studies

- Textured surfaces not ideal for laser annealing; difficult to control surface melting conditions. Stress buildup after annealing decreased V_{OC} substantially
- Surface cleanliness affects cell performance after laser anneal much more than it affects cell performance after thermal anneal. Particulates left on surface may form nucleation sites during laser anneal. Preferential etching confirmed this
- Optimum laser density determined to be between 1.4 J/cm^2 and 1.6 J/cm^2 . Energy densities outside these limits were characterized by poor fill factors and low V_{OC}
- Laser parameters that produced the best cells were: 1.4 to 1.6 J/cm^2 , 50% overlap, 25 nanoseconds pulse duration, 1 mm^2 spot size
- Ion implantation parameters that produced the best cells were: 5 keV implant energy, 1 to $2 \times 10^{15} \text{ atoms/cm}^2$ fluence

Excimer Laser Annealing

- Economic analysis
Assumptions:
1985 dollars
80% up time
0.886 yield
600 wafers/hour throughput
1850 hours/shift/year
3 shifts
100 mm diameter, as-cut, silicon wafers

Module Efficiency, %	PELA, \$/watt	Diffusion, \$/watt	Output, MW/yr
12	6.85	6.79	2.22
13	6.32	6.27	2.41
14	5.87	5.87	2.59
15	5.48	5.44	2.78
16	5.14	5.10	2.96

- Cell fabrication
Best $2 \times 2 \text{ cm}$ cell: 15.5%

Excimer Laser-Assisted Metal Deposition

Surface passivation

Goal: To deactivate the silicon dangling bonds at the surface

$$V_{oc} \propto \ln \frac{1}{U}$$

where U = rate of recombination

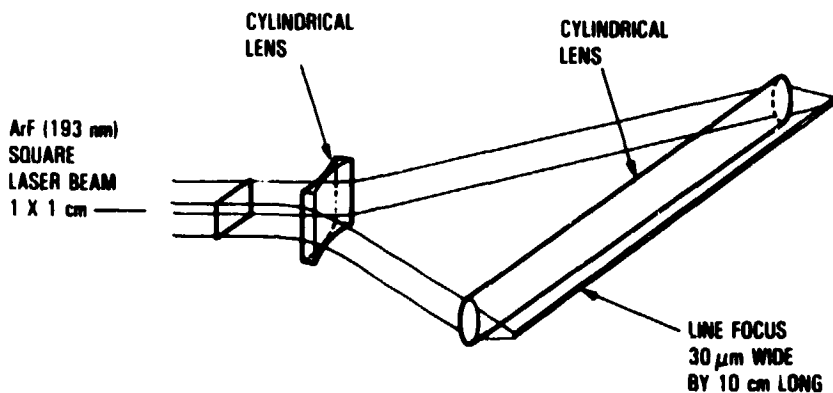
Conventional method: thermal oxide

Propose: Laser-assisted photochemical dissociation of oxide



Fine grid-line metallization

Goal: Laser-assisted metal deposition; eliminate "wet" steps in photolithography process. Process could also be applicable to thin-film solar cells

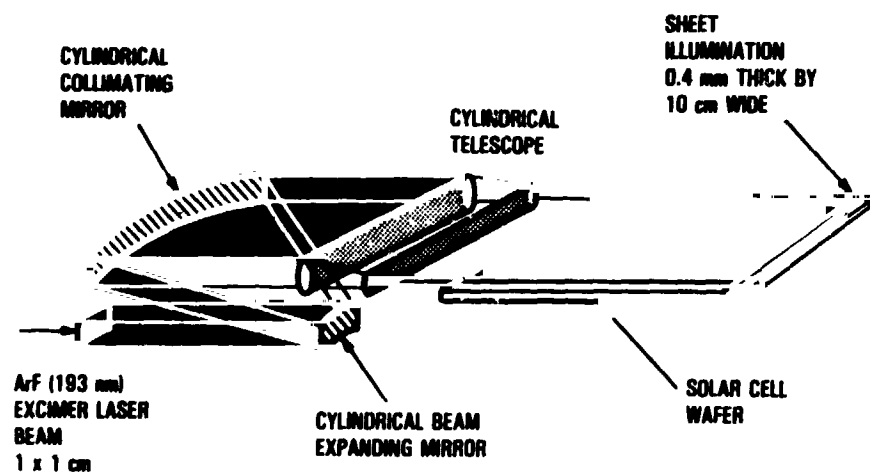


PLENARY SESSIONS

Excimer Laser-Assisted Film Deposition

Surface passivation (Continued)

Rate of deposition = 600-800 Å/min



Excimer Laser-Assisted Metal and Film Deposition

- Experiments have just started
- No data on metal and film deposition

PLENARY SESSIONS

Microwave-Enhanced Chemical Vapor Deposition System

Objective:

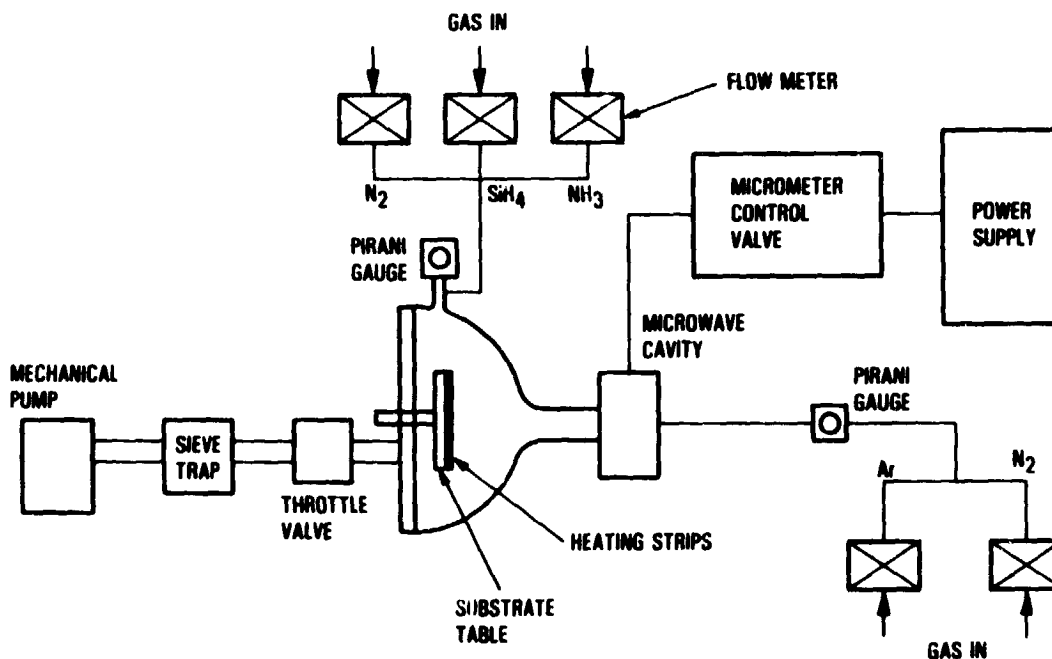
Design, fabricate and demonstrate a microwave-enhanced CVD system to show feasibility of depositing silicon nitride

Rationale:

Microwave-enhanced chemical vapor deposition of passivation coatings has the potential advantages of:

- Higher electron plasma density ($10^{13}/\text{cm}^2$ vs $10^9/\text{cm}^2$ for RF) where W_p is 2.45 GHz instead of 13.56 MHz
- Long lifetime in species, which allows reaction chamber and plasma generation chamber to be separated
- More control of deposition kinetics with less damage to substrate
- Controlling film gradients or doping profiles
- Lower power requirements
- Lower reactive gas consumption

Schematic of Microwave-Enhanced Chemical Vapor Deposition System



PLENARY SESSIONS

Results of Microwave-Enhanced Chemical Vapor Deposition

- Contractor effort completed
- Feasibility has been demonstrated; silicon nitride deposited using MECVD technique
- Adhesion problems noted and problem solved by substrate heating
- Film non-uniformity noted; possible solution involves hardware redesign for a more even reactant gas distribution
- Follow-on development effort desirable: funding problems

Laser-Assisted Metallization

A photolithographic system for fine line metallization employs sequential multistep process

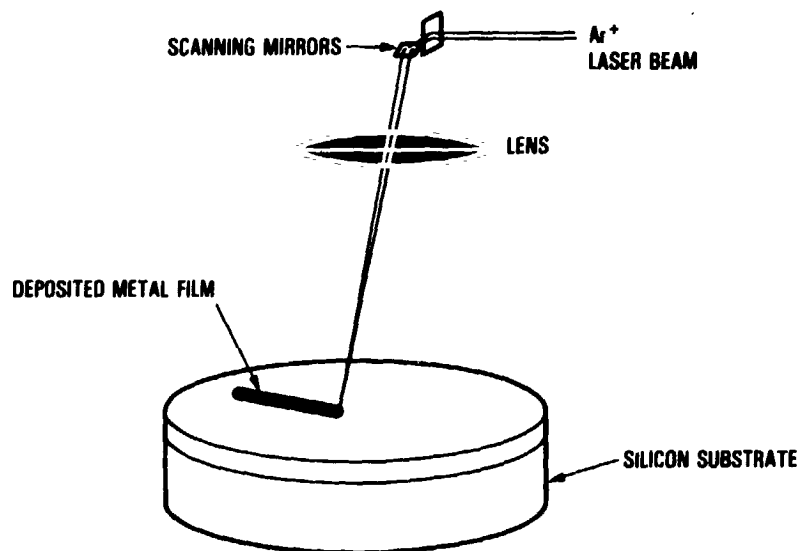
- Spin-on photoresist
- Bake
- Expose pattern
- Develop (remove polymerized layer)
- Rinse
- Vacuum evaporate metal
- Lift-off (remove excess metal and photoresist)
- Clean

Laser-assisted metallization steps are significantly reduced

- Cover cell with metal film (spin-on, vacuum evap., etc.)
- Laser-write on metal film
- Plate-up on "written" surfaces
- Remove excess metal film

PLENARY SESSIONS

Laser Pyrolysis of Spun-on Metallo-Organic Film



SAMPLE BASE TEMPERATURE 75°C
FOCUSED LASER SPOT DECOMPOSES SPUN-ON FILM
METALLIZATION PATTERNS ARE FORMED BY DIRECTWRITING

Lighted I-V Data

Photolithography Baseline	Short-Circuit Current, mA	Open-Circuit Voltage, V	Fill Factor	Efficiency, %
Best Cell	36.5	0.579	0.738	15.6
Average Cell	33.8	0.569	0.703	13.6
Worst Cell	30.1	0.566	0.670	9.7
Laser- Metallized				
Best Cell	36.1	0.589	0.776	16.5
Average Cell	33.9	0.576	0.766	15.0
Worst Cell	32.0	0.571	0.751	13.7

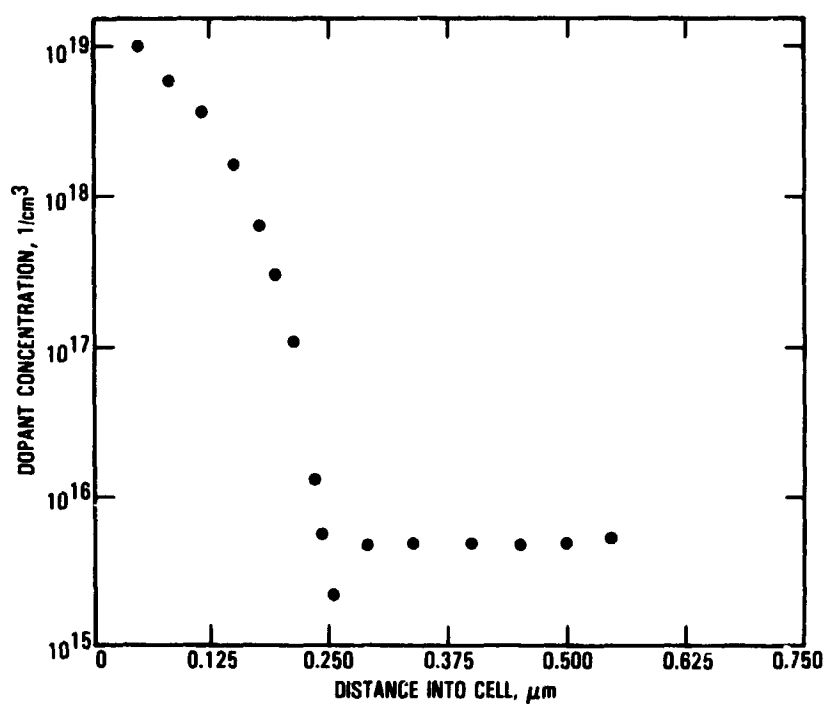
- High-quality solar cells obtained by laser metallization technique: AR-coated cell efficiency = 16.7%
- IN-SITU sintering occurs during laser writing process: low series resistance obtained with no further heat treatment
- Laser processing does not degrade solar cell characteristics: high shunt resistance and low leakage currents are achieved
- Higher efficiency possible by writing finer lines and optimizing grid pattern
- Program continuing to add high efficiency processes

Excimer Laser Drive-in of Liquid Dopants (Westinghouse)

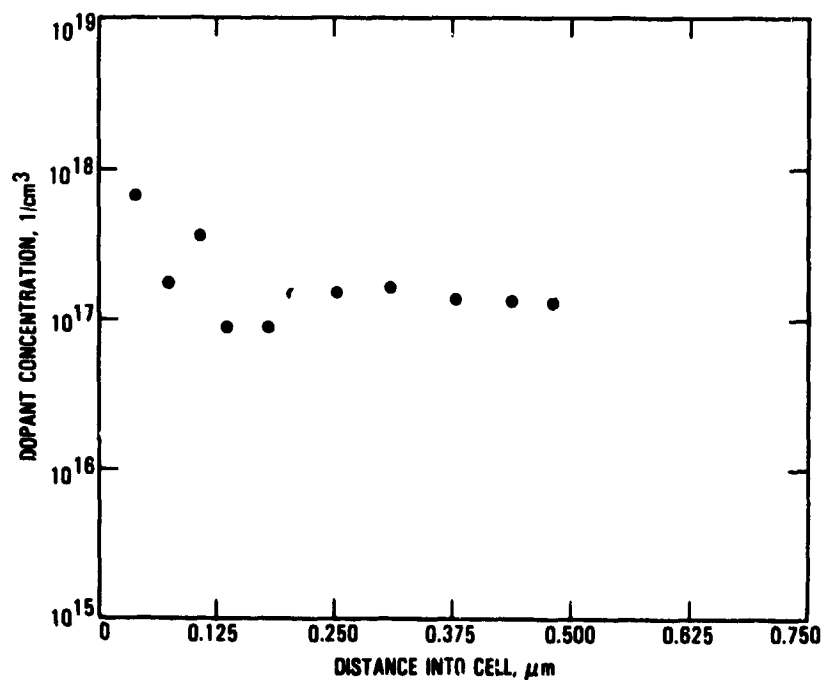
- Simultaneous drive-in of front and back junctions by thermal diffusion was unsuccessful. Cross-contamination of dopants occurred under all diffusion conditions using different diffusion masks. Cell efficiencies varied between <1% to 7 %
- Investigation of laser-drive-in of liquid dopants was started
- Three sets of web strips subjected to laser drive-in tests performed by Spectra Technology, Bellevue, Washington
- No cross-contamination of dopants occurred on any laser drive-in tests
- Front-junction profile looks good. See profile figure
- Back-junction profile is not good. See profile figure
- Laser parameters for front junction: 1.5 j/cm², 25 nanoseconds pulse duration, 1 mm² spot size, 50% overlap
- Laser parameter for back junction not yet established

PLENARY SESSIONS

n^+p Front Junction by Excimer Laser Drive-in



p^+p Back Junction by Excimer Laser Drive-in



PLENARY SESSIONS

Results and Status of Excimer Laser Drive-in of Liquid Dopants

- Best cells produced to date: 8% to 10% efficiency; inadequate back ohmic contact identified as cause of poor cell performance
- One final set of low-resistivity (0.4 ohm-cm) web strips to be subjected to laser drive-in tests. Back ohmic contact should be improved
- Successful demonstration of laser drive-in of liquid dopants will achieve the simultaneous junction drive-in goals
- Exploratory tests using rapid thermal processing (RTP) to simultaneously drive-in liquid dopants
- Initial results are very encouraging; 15% efficient cells produced
- Will conduct more tests to obtain statistical data

Application Potential

- **Excimer laser anneal (after ion implantation)**
 - **Near term (<3 yr):**

Not good. Only marginally equal to thermal anneal; probably will not supplant it
 - **Far term (3-15 yr):**

Fair. Has best chance if lasers are used in other parts of the process sequence
- **Laser-assisted metallization (laser writing) (pyrolytic)**
 - **Near term (<3 yr):**

Good potential for near-term use. Eliminates photolithography; immediate cost savings
 - **Far term (3-15 yr):**

Same good potential. May dominate metallization processes
- **Excimer laser drive-in of liquid dopants**
 - **Near term (<3 yr):**

Not good. Back-junction problems, needs more test evaluation
 - **Far term (3-15 yr):**

Not good. Must compete with rapid thermal processing (RTP)
- **Microwave-assisted deposition (MECVD)**
 - **Near term (<3 yr):**

Fair. Needs more evaluation
 - **Far term (3-15 yr):**

Good. Microwave-assisted techniques have good potential in other processes -i.e., baking, sintering
- **Laser-assisted deposition (photolytic)**
 - **Near term (<3 yr):**

(metal and surface passivation)
Cannot assess. No data available yet; may require extensive research
 - **Far term (3-15 yr):**

Cannot assess. May have good potential for amorphous silicon
- **Rapid Thermal Processing (RTP)**
 - **Near term (<3 yr):**

Good. Limited data very encouraging. Has good potential for junction formation and annealing
 - **Far term (3-15 yr):**

Good. May dominate ion implantation anneal